Application of sequence stratigraphic concepts to the Upper Cretaceous Tununk Shale Member of the Mancos Shale Formation, south-central Utah: Parasequence styles in shelfal mudstone strata

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ABSTRACT

Although sequence stratigraphic concepts have been applied extensively to coarse-grained siliciclastic deposits in nearshore environments, high-resolution sequence stratigraphic analysis has not been widely applied to mudstone-dominated sedimentary successions deposited in more distal hemipelagic to pelagic settings. To examine how sequence stratigraphic frameworks can be derived from the facies variability of mudstone-dominated successions, the Tununk Shale Member of the Mancos Shale Formation in south-central Utah (USA) was examined in detail through a combination of sedimentological, stratigraphic and petrographic methods. The Tununk Shale accumulated on a storm-dominated shelf during the second-order Greenhorn sea-level cycle. During this eustatic event, the depositional environment of the Tununk Shale shifted laterally from distal middle shelf to outer shelf, then from an outer shelf to an inner shelf environment. At least 49 parasequences can be identified within the Tununk Shale. Each parasequence shows a coarsening-upward trend via upward increases in silt and sand content, thickness and lateral continuity of laminae/beds, and abundance of storm-generated sedimentary structures. Variations in bioturbation styles within parasequences are complex, although abrupt changes in bioturbation intensity or diversity commonly occur across parasequence boundaries (i.e. flooding surfaces). Due to changes in depositional environments, dominant sediment supply and bioturbation characteristics, parasequence styles in the Tununk Shale show considerable variability. Based on parasequence stacking patterns, eleven system tracts, four depositional sequences and key sequence stratigraphic surfaces can be identified. The high-resolution sequence stratigraphic framework of the Tununk Shale reveals a hierarchy of stratal cyclicity. Application of sequence stratigraphic concepts to this thick mudstone-dominated succession provides important insights into the underlying causes of heterogeneity in these rocks over multiple thickness scales (millimetre-scale to metre-scale). The detailed sedimentological characterization of parasequences, system tracts and depositional sequences in the Tununk Shale provides conceptual approaches that can aid the development of high-resolution sequence stratigraphic frameworks in other ancient shelf mudstone successions.

Keywords Mudstone facies, mudstone petrography, sequence stratigraphy, storm-dominated shelf, Tununk Shale, Turonian, Western Interior Seaway.
INTRODUCTION

Sequence stratigraphy is the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or non-deposition, or their correlative conformities (Posamentier et al., 1988; Van Wagoner et al., 1988, 1990). This framework ties changes in stratal stacking patterns developed in response to variations in sediment supply and accommodation and provides the context within which evolution of depositional systems through space and time can be interpreted (Jervey, 1988; Posamentier & Allen, 1999; Catuneanu et al., 2009, 2011). Since the concepts of sequence stratigraphy were proposed in the 1970s, sequence stratigraphic methods have been widely applied to coarse-grained siliciclastic deposits in coastal and shallow-marine environments, owing to the potential of these rocks to form significant hydrocarbon reservoirs (e.g. Van Wagoner et al., 1990; Catuneanu et al., 2009). Because nearshore environments are sensitive to relative changes in sea level, sediments deposited in these environments are particularly suitable for high-resolution sequence stratigraphic analysis (Catuneanu et al., 2009; Reynolds, 2009).

Fine-grained sedimentary rocks (i.e. mudstones/shales that are composed mainly of particles smaller than 62.5 µm) constitute approximately two-thirds of the sedimentary rock record (Potter et al., 2005; Lazar et al., 2015), and they can serve as petroleum source rocks, unconventional hydrocarbon reservoirs and seals. In spite of the great economic significance of these rocks, high-resolution sequence stratigraphic analysis has seldom been attempted in mudstone-dominated successions deposited in more distal settings (for example, hemipelagic to pelagic) (e.g. Bohacs & Schwalbach, 1992; Bohacs, 1998; Macquaker et al., 1998, 2007; Schieber, 1998a). This state of affairs is due to the inherent difficulties that complicate detailed facies analysis of mudstones, such as susceptibility to weathering and largely cryptic variability in grain size and sedimentary features. Yet, notwithstanding these obstacles, a comprehensive understanding of sedimentary facies and their associations is essential for reliable interpretations of stacking patterns and sequence stratigraphic surfaces (Catuneanu, 2006). Nonetheless, many investigations of facies variability in fine-grained sedimentary successions rely heavily on data from mineralogical, geochemical, or palaeontological analyses (e.g. Ver Straeten et al., 2011; Ayranci et al., 2018), even though key information such as grain size, sedimentary textures, biogenic features and origin of different components cannot be directly obtained with these techniques (Macquaker et al., 2007).

Recent advances in flume experiments on mud transport and deposition (Schieber et al., 2007; Schieber & Southard, 2009; Schieber, 2011), as well as observations on modern muddy shelves (Rine & Ginsburg, 1985; Kuehl et al., 1986; Nittrouer et al., 1986; Wright et al., 1988; Kineke et al., 1996; Allison et al., 2000; Trayanovski et al., 2000), have shown that the processes responsible for mud deposition and formation of fine-grained sedimentary successions are much more dynamic than traditionally presumed. A growing number of case studies of ancient fine-grained sedimentary successions also show that mudstone successions, albeit appearing homogeneous in outcrops or cores, are characterized by small-scale cyclic facies variations (i.e. parasequences and parasequence sets) when examined in detail (Bohacs & Schwalbach, 1992; Macquaker et al., 1996, 1998, 2007; Macquaker & Taylor, 1996; Bohacs, 1998; Schieber, 1998a; Macquaker & Howell, 1999; Bohacs et al., 2005, 2014; Birgenheier et al., 2017; Wilson & Schieber, 2017). Their recognition poses the question as to what are the dominant processes that produce the complex variability observed in mudstones, and control the evolution of mud-dominated systems through space and time. To date, owing to the paucity of published studies of mudstone successions that have been comprehensively evaluated with sequence stratigraphic methods, many of these important questions remain unresolved.

For this study, the extensive exposures of the Upper Cretaceous Tununk Shale Member in south-central Utah afford an excellent opportunity to examine small-scale (parasequence-scale) facies variations within this ancient shelf mudstone succession, and enable understanding of the evolution of the depositional system through time and space within a sequence stratigraphic framework. The focus of previous studies of the Tununk Shale was mainly on regional stratigraphy, as well as mineralogical and geochemical characteristics. Chronostratigraphic correlations (bentonite beds) between the Tununk Shale in south-central Utah (Henry Mountains Region) with its lateral equivalent, the Tropic Shale in southern Utah (Kaiparowits Plateau) led to recognition of offshore prograding clinoform
parasequences, system tracts and sequences in stone-dominated succession. Characteristics of tidal sequences can be identified in a mud-derived parasequences, system tracts and depositional sequences in ancient shelf mudstone succession. This investigation also serves as a test case for how the Tununk Shale accumulating on a storm-dominated shelf was proposed (Li & Schieber, 2018a). This perspective is supported by the recognition that the dominant sediment dispersal mechanisms were storm-generated offshore-directed currents (across-shelf) and geostrophic currents (alongshelf), as illustrated by typical sedimentary facies and facies successions in the Tununk Shale (Li & Schieber, 2018a). The disparity between this and prior depositional models of the Tununk Shale indicates that the validity of previously described parasequences needs to be re-evaluated, because teasing out parasequences based solely on mineralogy is usually complicated by the fact that these rocks usually are composed of complex components (for example, allochthonous, autochthonous and diageneric-derived) in varying proportions (Macquaker et al., 2007; Aplin & Macquaker, 2011; Lazar et al., 2015). The recognition of parasequences based on an integrated analysis of variations in mineralogical composition, changes in grain size and sedimentary facies characteristics is clearly preferable (Van Wagoner et al., 1990).

The present study re-evaluated the Tununk Shale in south-central Utah via integrated sedimentological, petrographic and stratigraphic analyses, with the aim to develop a high-resolution sequence stratigraphic framework for this thick ancient shelf mudstone succession. This investigation also serves as a test case for how readily parasequences, system tracts and depositional sequences can be identified in a mudstone-dominated succession. Characteristics of parasequences, system tracts and sequences in the Tununk are described and summarized to this end, to provide a better understanding and guidance for the conduct of sequence-stratigraphic analysis of other shelf mudstone successions in the stratigraphic record.

GEOLOGICAL BACKGROUND

During the Late Jurassic and Cretaceous, the western interior of North America was occupied by an asymmetrical foreland basin that had developed in response to the flexural loading of the Sevier thrust belt (Kauffman, 1977, 1985; Livaccari, 1991; Kauffman & Caldwell, 1993; Liu et al., 2011; DeCelles, 2004). The combined effects of load-induced subsidence and global eustatic highstand throughout the Late Cretaceous resulted in the development of an epicontinental seaway known as the Western Interior Seaway (WIS; Kauffman, 1977, 1985). During the Albion to Maastrichtian, the WIS was subject to five major transgressive–regressive marine cycles with durations from 2 to 10 Myr (Kauffman, 1985); cycles that correspond in duration to second-order cycles, sensu Mitchum & Van Wagoner (1991). The most extensive flooding of the seaway occurred during the so-called Greenhorn cycle, when more than one-third of North America was inundated (Fig. 1A). The Greenhorn cycle began in the Late Albian and ended in the Middle Turonian (Kauffman, 1985). During peak transgression in the Early Turonian, the WIS extended from the Arctic Ocean to the Gulf of Mexico and was characterized by a broad shelf (Fig. 1A). The estimated water depth within this epeiric seaway never exceeded more than a few hundred metres water depth (Weimer, 1984; Kauffman, 1985; Sageman & Arthur, 1994). In response to sediments supplied from the unroofing of the Sevier orogenic belt and volcanic highlands to the west, the WIS was broadly characterized by high siliciclastic input and high sedimentation rates along the western margin, and little clastic input on the eastern margin (Kauffman, 1977, 1985; Hart, 2016).

The Upper Cretaceous succession currently exposed in central and southern Utah was deposited along the western margin of the WIS as a series of eastward-prograding clastic wedges (Fig. 1B). Deposition of the Tununk Shale occurred from the Late Cenomanian to the Middle Turonian over a time span of about 2.5 Myr (Zelt, 1985; Leithold, 1994). Driven by the Greenhorn transgressive–regressive sea-level
cycle, the offshore mudstones of the Tununk Shale overlie the coarser non-marine and paralic deposits of the Dakota Sandstone and grade upward into the shallow marine and deltaic strata of the Ferron Sandstone Member (Fig. 2; Peterson et al., 1980; Kauffman, 1985). During deposition of the Tununk Shale, the palaeoshoreline trended north-east/south-west in the study area (Fig. 1). Although the dominant direction of sediment progradation was eastward, nearshore sediments deposited along the western margin of the WIS were deflected southward by coastal currents generated by a large-scale counterclockwise gyre (Fig. 1; Barron, 1989; Ericksen & Slingerland, 1990; Slingerland & Keen, 1999; Li et al., 2015; Li & Schieber, 2018a).

Depositional framework of the Tununk Shale

In outcrop, the Tununk Shale is an approximately 200 m thick succession that is largely composed of dark grey calcareous to non-calcareous (argillaceous) mudstones with numerous thin silt-rich and sand-rich beds and volcanic ash beds (i.e. bentonites; Peterson...
et al., 1980; Zelt, 1985). In an integrated surface to subsurface study, Zelt (1985) utilized 17 traceable bentonite beds and biostratigraphic relationships to correlate the Tununk Shale in south-central Utah (Henry Mountains Region) with its lateral equivalent, the Tropic Shale in southern Utah (Kaiparowits Plateau; Figs 1B and 2).

Based on an integrated analysis of sedimentary facies and bioturbation characteristics, palaeocurrent data and palaeogeography, the sedimentology and depositional environments of the Tununk Shale are discussed in detail in a previous study (Li & Schieber, 2018a), and are only briefly summarized here. The Tununk Shale ranges in thickness from 170 to 210 m in the study area (Fig. 3) and is interpreted to be accumulated on a storm-dominated shelf. The sediments of the Tununk Shale were derived from multiple sources, including significant amounts of clastic sediments derived from the Sevier orogenic belt and volcanic highlands, primary productivity (for example, foraminifera tests, faecal pellets and coccoliths), wind-borne volcanic ash, and possibly from submarine erosion of the lacuna that had developed in north-eastern Utah (Fig. 1; Li & Schieber, 2018b). Based on the relative proportion between carbonate particles derived from primary productivity versus siliciclastic particles derived from terrigenous input, the Tununk Shale can be divided into four lithofacies packages including: (i) carbonate-bearing (<30% carbonate), silty and sandy mudstone (CSSM); (ii) silt-bearing, calcareous mudstone (SCM, >30% carbonate); (iii) carbonate-bearing, silty mudstone to muddy siltstone (CMS); and (iv) non-calcareous, silty and sandy mudstone (SSM) in an ascending order. Up-section, the relative amount of the carbonate component derived from primary productivity within the Tununk Shale gradually increases from the CSSM to the SCM facies, then decreases to the CMS facies, and becomes absent in the SSM facies. Details of sedimentary and biogenic features in each lithofacies package are summarized in Table 1 and are illustrated using the measured stratigraphic section at Salt Wash (Fig. 4). Vertical variations in lithofacies types and sedimentary facies characteristics indicate that the Tununk Shale shifted laterally from distal middle-shelf to outer-shelf (CSSM to SCM lithofacies), and then back from an outer-shelf to an inner-shelf setting (CSSM to SSM lithofacies) (Fig. 4; Table 1). Based on integrated analysis of palaeocurrent data and palaeogeography, storm-induced shore-parallel geostrophic flows and offshore-directed flows likely were the dominant processes that governed the transport and deposition of mud across and along this storm-dominated shelf (Li & Schieber, 2018a).
For this study, the Tununk Shale in the Henry Mountains region of south-central Utah (Fig. 3) was examined to collect data for comprehensive sedimentological and sequence stratigraphic analyses. Three detailed stratigraphic sections near Hanksville, Utah, extending parallel to the palaeoshoreline direction (north-east to south-west), were measured using a Jacob staff (1.5 m long) along a 30 km transect (Fig. 3). Because these rocks are highly susceptible to weathering, steep exposures were chosen and excavated where needed to reveal fresh rock for description and sample collection. For every 1.5 m Jacob staff interval, two small pits (up to several tens of centimetres in both depth and length) were dug in the lower third (0 to 0.5 m) and upper third (1.0 to 1.5 m) intervals to expose fresh rock. Relatively unweathered samples were collected at an average vertical spacing of 1 m (more closely spaced in some places). More than 500 samples, collected from three measured sections, were taken back to the laboratory, embedded in epoxy, slabbed and then polished. High-resolution images of polished slabs were acquired with a flatbed scanner (1200 to 2400 dpi resolution) and then contrast-enhanced in Adobe Photoshop™ to examine small-scale (millimetre-scale to centimetre-scale) sedimentary features and facies variability.

For each stratigraphic section, sedimentological data including lithology, grain size, sedimentary features, bioturbation features, and amount and types of fossil fragments were documented using the methodology of Lazar et al. (2015). In the field, grain-size variability was mainly determined by: (i) feeling and chewing rock samples to estimate silt versus clay (i.e. gritty versus smooth) content; and (ii) variations in colour. The relative percentage of silt estimated by chewing essentially mirrors the quartz-silt content and serves as a reliable proxy for grain-size distribution in mudstones that can be related to overall depositional
Table 1. Summary of sedimentary and biogenic features in each lithofacies package within the Tununk Shale (Li & Schieber, 2018a). Four lithofacies packages present in the Tununk Shale include: (i) carbonate-bearing, silty and sandy mudstone (CSSM); (ii) silt-bearing, calcareous mudstone (SCM); (iii) carbonate-bearing, silty mudstone to muddy siltstone (CMS); and (iv) non-calcareous, silty and sandy mudstone (SSM). Combining lithofacies with bioturbation intensity, a total of nine types of ‘shale microfacies’ (sensu Schieber & Zimmerle, 1998) are recognized in the Tununk Shale. These include CSSMm, CSSMh, SCMl, SCMm, CMSm, CMSh, SSMl, SSMm and SSMh (Fig. 5). The lower case letters ‘l’, ‘m’ and ‘h’ following each lithofacies name represent low, medium and high bioturbation intensity, respectively.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Depositional environment</th>
<th>Degree of clastic dilution</th>
<th>Sedimentary structures</th>
<th>Bioturbation characteristics</th>
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<tr>
<td>CSSM</td>
<td>Distal middle shelf</td>
<td>Moderate to small</td>
<td>Thin (&lt;1 mm to several millimetres) silt to sand lamina to lamina-sets showing starved-ripple cross-lamination (common) and a minor amount of wave ripple cross lamination. Commonly disrupted by burrows</td>
<td>Moderate to high bioturbation intensity (BI = 3–5), low trace-fossil intensity. Ichnogenera present: navichnia (sediment-swimmer traces), Phycosiphon, Chondrites and rare Planolites</td>
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<tr>
<td>SCM</td>
<td>Outer shelf</td>
<td>Small (minimum)</td>
<td>More common and laterally continuous calcareous and silt laminae to lamina-sets (&lt;1 mm to several centimetres). Typical sedimentary structures present include wave-ripple and combined-flow ripple lamination, and a small proportion of layers with normal grading, parallel lamination (both continuous and discontinuous), and starved-ripple cross-lamination</td>
<td>Low to moderate BI (1–4), low trace-fossil intensity. Ichnogenera present: navichnia, Phycosiphon and more common Fugichnia (escape structures) upsection</td>
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<tr>
<td>CMS</td>
<td>Middle shelf</td>
<td>Moderate to high</td>
<td>Common silt lamina to lamina-sets (thickness ranging from a few millimetres to several centimetres). Most primary sedimentary features are disrupted or absent due to pervasive bioturbation. Remnant preserved wave-ripple cross-laminations can be identified locally</td>
<td>Moderate to high BI (3–6) and trace-fossil diversity. Ichnogenera present: Phycosiphon, Chondrites, Planolites, Cylindrichnus, Teichichnus, Schaubcylindrichnus freyi, Zoophycos and Thalassinoidei</td>
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<tr>
<td>SSM</td>
<td>Inner shelf to distal lower shoreface</td>
<td>High (maximum)</td>
<td>Most silt/sand lamina to lamina-sets in this facies are sharp-based and range from a few to several centimetres in thickness (a few sandstone beds can be as thick as 14 cm in outcrop). A wide range of sedimentary structures are present including common wave-ripple lamination, combined-flow ripple lamination, hummocky cross-stratification (HCS), a small amount of starved ripple and current ripple lamination, normal (and rare inverse) grading, and local soft sedimentary deformation</td>
<td>Highly variable BI (0–6) and trace-fossil diversity. Ichnogenera present: Phycosiphon, Chondrites, Planolites, Schaubcylindrichnus freyi, Teichichnus, Thalassinoidei, Skolithos and Ophiomorpha</td>
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setting and relative changes of sea level (Williams et al., 2001; Li et al., 2015; Birgenheier et al., 2017). In the laboratory, grain-size parameters (size and distribution) were further calibrated by semi-quantitatively comparing petrographic and scanning electron microscope (SEM) photomicrographs of selected samples at a range of magnifications.

A variety of sedimentary structures (such as abundance and continuity of laminae, grading, ripple forms, scourcs, etc.) and biogenic features (trace fossil types and bioturbation intensity) were documented. The Bioturbation Index (BI) of Taylor & Goldring (1993) was used to characterize the bioturbation intensity in these rocks, and the terminology of MacEachern et al. (2007) was used to identify specific burrow types. A facies key that summarizes the various aspects of sedimentary and biogenic features documented in this study is shown in Fig. 5.

The facies scheme used in this study is summarized in Table 1 and presented in greater detail in Li & Schieber (2018a). To characterize the variations in the rock composition and textural characteristics throughout the Tununk Shale, 41 polished thin sections (20 to 25 μm thick) and 48 ion-milled samples (up to 12 mm diameter) were prepared from samples representing all lithofacies and microfacies types throughout three measured sections. Detailed petrographic examination of polished thin sections and ion-milled samples were conducted using a petrographic microscope and an FEI Quanta 400 SEM (FEI Company, Hillsboro, OR, USA). The SEM was operated at 15 kV and a working distance of 10 mm. Energy-dispersive X-ray spectroscopy was used to determine the composition and mineralogy of individual grains.

For sequence stratigraphic analysis, this study focused on the basic characteristics of parasequences, system tracts and sequences, and endeavoured to employ objective criteria for their recognition. Parasequences are the fundamental building blocks of depositional sequences. They occur in all system tracts and are characterized by distinctive upward-shallowing successions of relatively conformable beds and bedsets bounded by surfaces of flooding, abandonment or reactivation and their correlative surfaces (Van Wagoner et al., 1990; Catuneanu et al., 2009; Abreu et al., 2014). A parasequence set is a succession of genetically related parasequences forming a distinctive stacking pattern (for example, progradational, retrogradational and aggradational). Based on stratal stacking patterns, position within the sequence and types of bounding surfaces, different system tracts can be identified (Van Wagoner et al., 1990); specifically lowstand, transgressive and highstand system tracts (LST, TST and HST) (Vail, 1987; Van Wagoner et al., 1987). In addition a falling-stage system tract (FSST) has been identified in a number of studies (Hunt & Tucker, 1992; Posamentier et al., 1992). Key stratal surfaces that divide sequences into different system tracts include the sequence boundary (SB), the transgressive surface (TS), and the maximum flooding surface (MFS; Van Wagoner et al., 1990).

PARASEQUENCES, SYSTEM TRACTS
AND KEY STRATIGRAPHIC SURFACES
IN THE TUNUNK SHALE

Within each measured section, at least 49 parasequences can be identified in the Tununk Shale based on variations in average grain size, sedimentary facies, trace-fossil associations and bioturbation intensity. Parasequences range in thickness from 40 cm to 12 m, while the thickness of most (>80%) parasequences in the Tununk Shale ranges from 1 to 6 m. Based on parasequence stacking patterns (for example, progradational, aggradational and retrogradational), the 49 parasequences can be grouped into 11 system tracts, and four depositional sequences can be identified (Figs 4 and 6). Changes in parasequence stacking patterns are also reflected in the outcrops of the Tununk Shale, which are characterized by successive alternations between resistant ledges and non-resistant slopes (Fig. 7). The most resistant intervals in outcrops correspond to LSTs of sequences 2 to 4 and are laterally continuous between all three measured sections (Figs 4, 6 and 7). Because the lithofacies characteristics and stratal stacking patterns show little variability among all three measured sections (Fig. 6), only the stratigraphic section measured at Salt Wash is presented here in detail (Fig. 4). In the Tununk Shale in the present study area, the MFS of sequence 1 occurs slightly above the boundary between the SCM and the CSSM lithofacies. The surfaces that separate lithofacies CMS from lithofacies SCM and lithofacies SSM from lithofacies CMS correspond to the basal sequence boundaries of sequences 3 and 4, respectively (Figs 4 and 6).
The following section will describe and summarize parasequence styles in the four depositional settings (inner to outer shelf) represented by the aforementioned lithofacies packages (Table 1). Focus is on the parasequence expression in the CSSM lithofacies using sequence 1 TST, in the SCM lithofacies using sequence 2 LST, in the CMS lithofacies using sequence 3 LST, and in the SSM lithofacies using sequence 4 LST. In addition, how parasequences in the TSTs and HSTs differ from those in the LSTs are described briefly and the overall stacking patterns in each sequence are discussed.

Sequence 1 (distal shelf to outer shelf environment)

In the study area, the Tununk Shale disconformably overlies non-marine and paralic deposits of the Dakota Sandstone. The base of the Tununk Shale is characterized by a conglomeratic layer containing pebbles of chert and fine-grained quartzite (Eaton et al., 1990), overlain by a regionally extensive oyster coquina containing *Pycnodonte newberryi* (Stanton) (Fig. 8). The conglomeratic layer was interpreted as deposited during subaerial exposure of the study area in response to base-level fall (Eaton et al., 1990). The oyster coquina represents a transgressive lag deposit that formed during the subsequent base-level rise when the conglomerate was reworked on a ravinement surface (Eaton et al., 1990; Gardner & Cross, 1994). Bentonite beds T1 and T2 which are present in the laterally equivalent Topic Shale in southern Utah do not occur in the basal Tununk Shale of the Hanksville study area (Figs 2 and 4; Zelt, 1985; Leithold, 1994). The disconformity at the base of the Tununk Shale, therefore, represents a composite surface where a sequence boundary (SB) is combined with a transgressive surface (TS) of marine erosion.

Above the TS lies the TST of sequence 1 (S1), which consists of CSSM lithofacies deposited on the distal middle shelf (Fig. 4; Table 1). In this setting parasequences are characterized by a slight coarsening-upward trend that is recorded by upward increases in the silt/sand content and the abundance of silty/sandy laminae...
Fig. 9. Parasequence thickness ranges from around 0.7 to 5.9 m, with an average of 2.4 m (Fig. 10). Bioturbation intensity is moderate to high throughout a parasequence. Common trace fossil types include navichnia (sediment-swimmer traces), *Phycosiphon*, *Chondrites* and rare...
Planolites (Fig. 11A and B). Within this context, lower portions of parasequences are commonly characterized by discontinuous or disrupted silty/sandy laminae (Fig. 11A). Upward, distinctive sedimentary features including starved current ripple and starved wave ripple cross-laminations become more common (Fig. 11B).

Silt-sized to sand-sized particles in the CSSM lithofacies are dominated by detrital grains (for example, quartz and feldspar), with a minor amount of biogenic carbonate particles such as foraminifera tests (dominantly planktonic), faecal pellets (composed almost exclusively of coccolith debris) and shell fragments (principally inoceramid bivalve fragments) (Fig. 12A and B). The foraminifera tests are mostly filled with calcite spar and minor or trace amounts of pyrite and authigenic clays including kaolinite and smectite (Fig. 12B). Parasequence sets of the TST show a retrogradational stacking pattern characterized by thinner and finer parasequences upward (Figs 4 and 12). Over the course of the TST, the CSSM lithofacies grades upward into SCM lithofacies (Fig. 11C), and the

**Fig. 7.** The outcrops of the Tununk Shale are characterized by successive alterations of resistant ledges and non-resistant slopes, which are due to variations in average grain size and dominant lithology. The resistant ledges in outcrops that represent the lowstand system tracts (LSTs) of sequence 2, 3, and 4 (Fig. 5) are highlighted in yellow, green and blue boxes, respectively, and are laterally continuous in the study area. Each LST consists of one to multiple coarsening-upward parasequences. Parasequence boundaries (flooding surfaces) are indicated by blue arrows. See Fig. 3 for locations of measured sections and Fig. 6 for the thickness of LST parasequences of different sequences. SW: Salt Wash, NCa: North Caineville, SCa: South Caineville.
relative amount of silt-sized to sand-sized detrital particles gradually decreases as biogenic calcareous particles increase (Fig. 12D and E). The fine-grained matrix also becomes more calcareous upward due to increasing amounts of coccoliths (Fig. 12F). Whereas BI may remain moderate to high, trace-fossil diversity and burrow size gradually decrease upward towards the MFS (Fig. 11C).

Other than lithology, HST parasequences are similar to those of the TST (Fig. 9) in S1. The HST parasequences consist of the SCM lithofacies and range from 1 to 5 m in thickness (Fig. 10). The coarsening-upward trend of parasequences is expressed in the upward increase of the abundance and lateral continuity of wavy laminae, which are made dominantly of silt-sized to sand-sized calcareous particles such as foraminifera tests (dominantly planktonic), faecal pellets and shell fragments (Figs 9 and 11D). The BI remains moderate throughout a given parasequence but may decrease slightly towards the top of a parasequence when wavy laminae become more common (Fig. 9). The HST parasequences are characterized by overall low trace-fossil diversity, similar to the TST (Fig. 11C and D).

**Sequence 2 (outer shelf environment)**

Sequence 2 (S2) consists of the SCM lithofacies deposited in the outer shelf environment (Fig. 4; Table 1). The basal SB of S2 is capped by a thin (a few millimetres or less) lag layer of broken inoceramid fragments at the base of a ca 5 cm wave-rippled bed. Above the SB, the LST in S2 consists of one parasequence, which shows an abrupt increase in the abundance of resistant layers in outcrops (Figs 6 and 7). The thickness of the LST parasequence ranges from 50 cm to 4.3 m, with an average of 2.4 m among three measured sections. Compared to the underlying HST of S1, LST parasequences in S2 show more common and distinct (thicker and more laterally continuous) storm-generated sedimentary structures such as parallel to slightly wavy laminae, wave ripple and combined-flow ripple laminations (Fig. 13). In the LST, the lower part of a given parasequence shows common bioturbation and few distinct sedimentary features (Fig. 14A), whereas the upper part shows an increasing amount of thicker (up to several centimetres) wave ripple and combined-flow ripple laminations and lower BI (Fig. 14B to D). Trace-fossil diversity remains low in the S2 LST.

In the lower part of a typical LST parasequence, silt-sized to sand-sized carbonate particles such as faecal pellets, foraminifera tests and shell fragments are commonly scattered in the fine-grained calcareous matrix (rich in coccolith debris; Fig. 15A). Towards the top of a given LST parasequence, these silt-sized to sand-sized carbonate particles are more prone to be concentrated along wavy laminae and show preferred orientation (Figs 14B to D and 15B to F). Wave ripple and combined-flow ripple laminations
Fig. 9. Schematic drawings of parasequence styles in sequence 1. See Fig. 5 for facies key.

Fig. 10. Box plot showing the distribution of parasequence thickness in different system tracts of the Tununk Shale. Data of parasequence thickness were compiled from all three measured sections. Note that outliers with excessive thickness tend to occur in S2 HST, S3 TST, and S4 TST. It is possible that each of these thick parasequences (outliers) actually consists of more than one thinner parasequences. Because TST and HST deposits are usually more fine-grained and more susceptible to weathering (non-resistant slopes in Fig. 7), thin parasequences are not as readily resolved. Therefore, the total number of parasequences documented in each measured section may underestimate the actual number of parasequences in the Tununk Shale. LST, lowstand system tract; TST, transgressive system tract; HST, highstand system tract.

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made dominantly of foraminifera tests tend to be better cemented by early diagenetic calcite close to the top of a parasequence, forming resistant layers in outcrops (Fig. 15E and F).

The TST parasequences of S2 are characterized by an abrupt decrease in the abundance of calcareous and silty laminae and an increase in BI (Figs 13 and 14E). Parasequences of the early HST of S2 are similar to those in the HST of sequence 1. Towards late HST in S2, parasequences show a gradual increase in the abundance and thickness of wave ripple laminations, trace-fossil diversity and burrow size up-section (Figs 13 and 14F).

Sequence 3 (middle shelf environment)

The SCM lithofacies abruptly changes into the CMS lithofacies across the SB at the base of sequence 3 (S3). The LST in S3 consists of three parasequences, and range from 2.0 to 6.7 m in thickness, with an average of 4.2 m (Fig. 10). Compared to S2, parasequences in the LST of S3 are characterized by moderate to high BI and a distinctly higher trace-fossil diversity (Figs 16 and 17). Common types of trace fossils in this facies are those produced by deposit-feeding organisms such as Phycosiphon, Chondrites, Planolites, Schaubcylindrichnus freyi, Cylindrichnus, Zoophycos and Thalassinoides (Fig. 17). The CMS lithofacies is characterized by significantly higher amounts of detrital silt particles and clays, and a subordinate amount of carbonate particles of biogenic origin (Fig. 18A to C). Although primary sedimentary features are commonly disrupted, remnant wave ripple laminations made dominantly of silt-sized detrital grains become thicker and more common upward within the LST parasequences (Figs. 17A, 17B and 18A to C).
Parasequences in the TST of S3 show moderate bioturbation to complete homogenization and much fewer remnant wave ripple laminations (Figs 16 and 17C). The MFS in S3 is characterized by a carbonate concretionary layer containing abundant broken fossil fragments and phosphatic particles (Fig. 17D). Above the MFS, bioturbation intensity remains moderate to high (BI = 3 to 6) in the HST (Fig. 16). Trace-fossil diversity, as well as the abundance of storm-generated sedimentary structures, gradually increases upward during...

Fig. 12. (A) Photomicrograph (cross-polarized light: CPL) showing a starved ripple lamina in the CSSMm facies in the transgressive system tract (TST) of S1. The lamina is made dominantly of silt-sized to sand-sized detrital grains (quartz and feldspar showing low interference colour) and a minor amount of biogenic carbonate particles (high interference colour). (B) Photomicrograph showing a representative view from the same sample of (A). Silt-sized to sand-sized particles include a dominant amount of quartz and feldspar and a minor amount of foraminifera tests (indicated by red arrows). The foraminifera tests are mostly filled with calcite spar and minor or trace amounts of pyrite and authigenic clays including kaolinite and smectite. (C) Photomicrograph showing a representative view of the fine-grained matrix in the CSSMm facies in the TST of S1. The fine-grained matrix is dominated by fine-grained detrital silt (mostly quartz) and clays and a small amount of coccolith debris. (D) Photomicrograph (CPL) showing the mottled texture in the SCMm facies close to the maximum flooding surface (MFS) in S1. Silt-sized to sand-sized particles in this facies consist of a major proportion of carbonate particles (particles showing high interference colour). The fine-grained matrix consists dominantly of coccolith debris (thus showing brighter interference colour compared to (A)). (E) The SCMm facies close to the MFS in S1 consists of a dominant amount of biogenic carbonate particles including foraminifera tests filled with calcite (red arrows) and faecal pellets (white dashed lines). The average grain size of detrital particles (darker grey) is distinctly finer compared to (B). (F) A representative view of the fine-grained matrix in the SCMm facies close to the MFS in S1. Note the abundant coccolith debris. Q, quartz; K-spar, potassium feldspar; Bio, biotite. (B), (C), (E) and (F) were taken in backscatter electron mode.
the HST (Fig. 17E). Due to common bioturbation, the coarsening-upward trend of parasequences is not always easy to recognize in outcrop, especially in the TST and HST. Although the relative proportion of carbonate particles derived from primary productivity is low overall, certain horizons in S3 are characterized by abrupt increases in carbonate content. These layers are typically better cemented by early diagenetic calcite and can also be associated with carbonate concretion layers, or concentration of fossil fragments (Figs 16, 17D and 18D to F). All of these features tend to occur in the intervals below flooding surfaces.

**Sequence 4 (inner shelf environment)**

The basal SB of sequence 4 (S4) shows minor erosional features (erosional base of a...
centimetre-scale wave-rippled bed) and separates the CMS lithofacies from the overlying SSM lithofacies. The LST in S4 consists of five or six parasequences. The thickness of parasequences in the LST ranges from 0.8 to 6.4 m, with an average of 3.1 m (Fig. 10). Parasequences in the LST of S4 contain a distinctly high proportion of detrital siltstone and sandstone beds, as well as a wide variety of storm-generated sedimentary structures (Fig. 19). A typical LST parasequence can be divided into three intervals (Fig. 19). The lower part is characterized by slightly bioturbated mudstones with thin (millimetres to a few centimetres) siltstone/sandstone beds (Fig. 20A). The middle part of a parasequence is characterized by moderately bioturbated sandy mudstones, with disrupted but still recognizable storm-generated sedimentary structures (Fig. 20B). The uppermost part of a parasequence shows low BI, and more common and thicker sandstone beds containing wave ripple laminations or hummocky cross-stratification (HCS) (Fig. 20C and D). Although these three intervals may not be present in every given parasequence, a general coarsening-upward trend can always be observed. Upward in a parasequence, the dominant trace-fossil types usually change from dominant deposit-feeding traces (for example, Phycosiphon, Chondrites, Planolites, Schaubcylindrichnus freyi, Teichichnus, etc.) to more common suspension-feeding traces (for example, Skolithos and Ophiomorpha) (Fig. 19). In S4, the SSM lithofacies contains almost exclusively siliciclastic particles derived from terrigenous sources and only a small amount of reworked fossil fragments (Fig. 21).

The TS capping the LST in S4 is characterized by a carbonate concretion layer (Fig. 20E). Parasequences in the overlying TST become thinner and finer (less silt and sand content) upward. Although storm-generated sedimentary structures such as silty/sandy wave ripple and
combined-flow ripple cross-laminations may still be common in a given parasequence, their thicknesses distinctly decreases upward in the TST (Fig. 19). Locally, soft sedimentary deformation features are observed in the TST (Fig. 20F). Compared to the LST, bioturbation intensity and diversity slightly decrease, whereas the relative amount of fossil fragments increases in the TST (Figs 4 and 19). The MFS in S4 is characterized by a very fine-grained sandstone bed showing planar and wave ripple laminations and enrichment of phosphatic particles, fish debris and bone fragments (Fig. 20G). Above the MFS, parasequences in the HST are characterized by moderate to high BI and common remnants of silty/sandy laminae (Fig. 20H). Remnant wave ripple and combined-flow ripple cross-laminations are more likely to be

Fig. 15. Petrographic characteristics of the LST parasequence in S2. (A) Photomicrograph (CPL) showing the bioturbated texture of the SCMm facies in the lower interval of the LST parasequence. Carbonate particles including foraminifera tests (red arrows), faecal pellets (white arrow) and shell fragments (high interference colour) dominate over detrital grains. The foraminifera tests are mostly filled with calcite spar. (B) and (C) Photomicrographs (PPL: plane-polarized light and CPL) showing SCMl facies from the upper interval of the LST parasequence (darker intervals in Fig. 14B and C). Note that sand-sized faecal pellets (white arrows) and foraminifera tests are concentrated along laminae and show preferred orientation. (D) Photomicrograph (CPL) showing a representative view of the wave ripple lamination close to the top of the LST parasequence. The lighter and darker layers consist dominantly of silt-sized/sand-sized foraminifera tests (filled with calcite spar) and faecal pellets, respectively. (E) and (F) Photomicrographs (backscatter and secondary electron mode) showing a representative view of the wave ripple lamination close to the top of the LST parasequence. The lamina is made dominantly of silt-sized to sand-sized foraminifera tests (red arrows), carbonate shell fragments (Ca), a minor amount of detrital grains (mostly quartz), and pervasive calcite cement (cc). The concentration of these carbonate particles along wavy laminae indicates that they were reworked by storm-induced bottom currents. Q, quartz.
preserved towards the top of a parasequence (Fig. 19). In some parasequences, carbonate concretions are present below, or are immediately overlain by, the flooding surfaces (Fig. 19).

Towards the late HST, remnant sandy wave ripple cross-lamination, as well as terrestrial organic matter become more common in parasequences up-section (Fig. 4).
DISCUSSION

Parasequence styles in the Tununk Shale

Parasequences formed in different depositional environments of the Tununk Shale show considerable variability in terms of lithofacies, sedimentary facies and bioturbation characteristics. During the initial Greenhorn transgression, sediment supply to the Tununk Shale was still dominated by siliciclastic components from the terrigenous input and had a minor amount of biogenic carbonate particles (Fig. 12A to C). In the distal middle shelf environment (S1 TST), coarsening-upward parasequences are characterized by upward increases in the amount of silt-sized/sand-sized detrital grains and sedimentary structures generated by bottom currents (for example, starved ripple and wave ripple laminations) (Figs 9, 11A and 11B). The moderate to high bioturbation index (BI) and low trace-fossil diversity indicate an overall slow sedimentation rate and some degree of environmental stress, mainly associated with the increasing water depth during the Greenhorn transgression.

Above the maximum transgression of the Greenhorn cycle, parasequences formed in the outer shelf environment (S1 HST to S2 HST) consist dominantly of carbonate particles derived from primary productivity and a minor amount of siliciclastic particles from terrigenous input (Fig. 15A to D). The coarsening-upward trend of parasequences in this environment is again reflected by an upward increase in the abundance of wave ripple or combined-flow
ripple laminations, which nonetheless consist mostly of silt-sized/sand-sized carbonate particles such as foraminiferal tests, faecal pellets and shell fragments (Figs 13 to 15). Although being originally settled to the sea bottom from the upper water column, these silt-sized/sand-sized carbonate particles are hydrologically equivalent to quartz silt grains (Nowell et al., 1981; Minoura & Osaka, 1992; Oehmig, 1993). The concentration of these carbonate particles along wavy laminae and wave ripple cross-lamination, as well as lower BI, towards the top of a given parasequence indicate that they were subject to more frequent reworking by storm-induced bottom currents owing to the shallowing of water depth (MacEachern et al., 2005). Comparable observations have also been made in the Cretaceous Eagle Ford Shale of south-western Texas, USA (Schieber et al., 2016), and in the Turonian sediments from Tanzania (Wendler et al., 2016). Trace-fossil diversity in this environment remained low, mainly related to relatively high sea level and oxygen/food limitation during the second-order Greenhorn highstand (Savrda & Bottjer, 1991; Li & Schieber, 2018a).
Fig. 19. Schematic drawings of parasequence styles in sequence 4. See Fig. 5 for facies key and Fig. 10 for ranges of parasequence thickness in different system tracts.
During the regressive phase of the second-order Greenhorn cycle, parasequences formed in the middle shelf environment (S3) consist dominantly of detrital silt grains and a minor amount of carbonate particles derived from primary productivity (Fig. 18A to C). The moderate to high BI, as well as increases in BI and burrow size in the CMS lithofacies indicate more favourable substrate conditions related to shallowing water depth. Due to pervasive bioturbation, the coarsening-upward trends of parasequences in this setting are more difficult to identify. However, the preserved remnants of wave ripple laminae become more common towards the top of a given parasequence, consistent with a slight increase in sedimentation rate (Fig. 16).

During continued regression of the second-order Greenhorn cycle, parasequences formed in the inner shelf environment (S4) consist almost exclusively of siliciclastic grains of terrigenous origin (Fig. 21A to D). Due to comparatively shallow water depth in the inner-shelf environment, the coarsening-upward trends of parasequences are well marked by upward increases in thickness and abundance of silty and sandy beds with storm-generated sedimentary structures (for example, wave ripple and combined-flow ripple cross-lamination, HCS) (Fig. 19). No
simple trend can be summarized to describe changes in bioturbation intensity or diversity within these parasequences. To illustrate this complexity, lowstand system tract (LST) or highstand system tract (HST) parasequences in S4 could be taken as examples. These parasequences can be subdivided into three intervals (Fig. 19). The relatively low bioturbation intensity and diversity in the lower part of a given parasequence may be due to increased water depth after flooding, resulting in diminished oxygen supply or reduced nutrient/food availability (Savrda & Bottjer, 1991). Increases in BI, trace-fossil diversity and burrow size in the middle part can be interpreted to reflect improving bottom water oxygenation as water depth decreases, and frequency and magnitude of erosive depositional events are still low. The upper part of a given parasequence usually shows low BI, probably a reflection of increased sedimentation rate and more frequent and stronger storm events (Bentley & Nittrouer, 2003; Wheatcroft & Drake, 2003; MacEachern et al., 2005). Similarly, parasequences developed in relatively proximal settings in the Mowry Shale, USA (latest Albian to earliest Cenomanian) can also be divided into three distinct intervals based on comparable trends in both sedimentary facies and bioturbation characteristics (Bohacs et al., 2005). In proximal areas, the complex changes in bioturbation intensity and diversity within parasequences indicate that bioturbation is controlled by multiple factors such as oxygen and food supply, substrate type, sedimentation rate, etc. (Savrda & Bottjer, 1991; Bohacs et al., 2005; MacEachern et al., 2005). Notwithstanding these complexities, abrupt changes in BI or dominant trace-fossil types commonly occur across parasequence boundaries.

In all depositional sequences recognized in the Tununk Shale in this study, LST parasequences are marked by comparatively high abundance of distinct (relatively thick and laterally continuous) storm-generated sedimentary features (regardless of dominant mineralogy) and comparably low BI. The TST parasequences are characterized by overall common bioturbation, a minimal amount of remnant sedimentary features...
and the lowest trace-fossil diversity. Bioturbation is also common in HST parasequences, but trace-fossil diversity, as well as the abundance of preserved remnants of storm-generated features gradually increases upward during the HST. In each sequence, TST parasequences have the smallest average thickness (Fig. 10), consistent with minimal sedimentation rate due to a longer transport pathway from the palaeoshoreline as a result of rising sea level. The average thickness of LST parasequences is smaller than that of HST parasequences in each sequence (Fig. 10). Based on sedimentary facies and bioturbation characteristics in LSTs and HSTs, this probably reflects more common reworking and erosion because of shallower water depth.

Identification of key sequence stratigraphic surfaces in the Tununk Shale

In this study, sequence boundaries and transgressive surfaces are more readily identified than maximum flooding surfaces. This is because LSTs in the Tununk Shale show resistant ledges in outcrop (Fig. 7) and the highest amount of storm-generated sedimentary features in each sequence (Figs 4 and 6). The abrupt increase in the abundance and thickness of storm deposits in the LSTs indicates that LSTs were deposited during periods of the shallowest water depth in each sea-level cycle. In the Tununk Shale, the basal sequence boundaries (SBs) of sequences 2 to 4 show minor erosional features such as thin lags of broken shell fragments or erosional bases of centimetre-thick wave ripple laminations, which are interpreted as minor hiatuses resulting from bottom scour by storm events (Schieber, 1998b). Nonetheless, the strata underlying and overlaying the SBs are largely conformable. Therefore, in the Tununk Shale, the SBs at the bases of LSTs are interpreted as the correlative conformity developed at the lowest relative point of sea level, sensu Hunt & Tucker (1992).

Across the transgressive surfaces (TSs) in all sequences in the Tununk Shale, the abundance and thickness of storm-generated sedimentary features abruptly decreases. Trace-fossil diversity tends to decrease as well, whereas BI increases to some degree in the TST compared to the underlying LST. The retrogradational shift of facies across TSs indicates rising sea level, which results in decreasing frequency and magnitude of storm reworking and lower sedimentation rates, and therefore cumulatively enhances the lowest trace-fossil diversity. Bioturbation is also common in HST parasequences, but trace-fossil diversity, as well as the abundance of preserved remnants of storm-generated features gradually increases upward during the HST. In each sequence, TST parasequences have the smallest average thickness (Fig. 10), consistent with minimal sedimentation rate due to a longer transport pathway from the palaeoshoreline as a result of rising sea level. The average thickness of LST parasequences is smaller than that of HST parasequences in each sequence (Fig. 10). Based on sedimentary facies and bioturbation characteristics in LSTs and HSTs, this probably reflects more common reworking and erosion because of shallower water depth.

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Maximum flooding surfaces are more difficult to identify in the Tununk Shale, in part because the intervals around the MFSs tend to be fine-grained, and thus prone to significant weathering that hides these features under debris. The cryptic nature of MFSs in the Mancos Shale (Campanian age) is also noted by Macquaker et al. (2007). In this study, maximum flooding surfaces are identified based on several criteria. Firstly, the MFS in each sequence can be determined at the point where parasequence stacking patterns change from retrogradational to progradational or aggradational. Therefore, MFS can be picked at the turnaround point by looking for an increase in average grain size, storm-generated sedimentary features, trace-fossil diversity and burrow size. Secondly, in the lower calcareous part of the Tununk Shale (especially for S1 and S2), the carbonate content derived from primary productivity in the Tununk Shale is primarily controlled by the degree of clastic dilution of the sediment input from primary productivity (coccoliths, foraminifera tests and faecal pellets). Therefore, the MFSs in S1 and S2 are associated with the highest carbonate content derived from primary productivity in each sequence, reflecting minimal clastic dilution at times of maximum relative sea level. Thirdly, features like well-cemented layers, carbonate concretion layers
and concentrations of fossil fragments or phosphatic particles are commonly related to periods of sediment condensation (overall low sedimentation rate or constant winnowing by bottom currents) during the rapid sea-level rise (Kidwell, 1986; Loutit et al., 1988; Macquaker et al., 1996; Taylor & Macquaker, 2014; Li & Schieber, 2015; Föllmi, 2016). These features are particularly useful for identifying maximum flooding surfaces in S3 and S4. Although the TSs and MFSs in the lower carbonate-rich sequences (S1 and S2), as well as in the upper siliciclastic-dominated sequences (S3 and S4), are all associated with intervals that show abrupt increase in carbonate content, it is critical to be cognisant of the fact that carbonate can be derived from different sources (primary input versus diagenetic cementation) and therefore has different implications for the depositional conditions (see next section for a more detailed discussion).

Above the MFSs, HST parasequences in each sequence show an overall up-section increase in the abundance of storm-generated sedimentary features, trace-fossil diversity and burrow size. The progradational stacking pattern of HST parasequences is interpreted as a result of decreasing water-depth, better water oxygenation and increased nutrient/food availability during the general shallowing of sea level and regression in each sequence. In some studies, degradational parasequence sets (forced regression) that follow the normal regression implicit in HSTs have been described as falling-stage system tracts (FSST) (Posamentier et al., 1992; Posamentier & Allen, 1999). The transition from the normal regression of the HST to the forced regression of the FSST is also represented by a correlative conformity (sensu Posamentier & Allen, 1999), but whether any of these are present in the Tununk Shale presents a challenge under the best of circumstances and cannot be determined with any degree of certainty from the data collected for this study. Therefore, the FSST is not included here, but it is noted that the overall regressive trend of the HSTs in the Tununk Shale may consist of both normal and forced regressive elements (Figs 4 and 6).

Comparing sedimentological–petrographic with mineralogy based sequence stratigraphic analysis

In an earlier study, based on detailed analyses of grain size (i.e. content of the non-calcareous coarse silt and sand) and mineralogy (i.e. weight percent of carbonate), at least 37 parasequences and six sequences were identified in outcrops of the Tropic Shale along the southern edge of the Kaiparowits Plateau and in the Tununk Shale of the southern Henry Mountains region (Leithold, 1994). The six sequences are described as third-order transgressive–regressive cycles (cycles 1 to 6), within which the MFSs are identified as the most calcareous horizons in each sequence (Leithold, 1994). In general, cycle 3 to cycle 6 identified in Leithold (1994) correspond to sequence 1 to sequence 4 in this study, respectively. In the present study area, cycle 1 and cycle 2 as documented from the Kaiparowits Plateau area are not preserved owing to the disconformity at the base of the Tununk Shale. Despite the overall consistency between Leithold (1994) and this study regarding the third-order sea-level cycles, distinct differences exist between the sequence stratigraphic frameworks of the two studies.

The most distinct difference is the designation of the surface capping the S2 LST in this study. As described before, the LST parasequence of S2, which lies above T5 and has a thickness of 1 to 2 m, is characterized by moderate and low bioturbation intensity in the lower and upper part, respectively (Fig. 13). The same trend in BI is also documented for the 1 to 2 m interval above T5 in Leithold (1994) and Sethi & Leithold (1997). The surface capping this parasequence was previously identified as a MFS based on: (i) the highest weight percent carbonate measured in this sequence; and (ii) minimal BI, which was interpreted to reflect minimum oxygen level (preserved laminae were not disrupted by burrows) during maximum transgression (Leithold, 1994). In this study, with additional observations of sedimentological and petrographic characteristics, the upward decrease in BI is interpreted to be due to higher sedimentation rate, revealed by more abundant and thicker wave ripple and combined-flow ripple laminae upward in the parasequence (Fig. 14A to D). These storm-generated sedimentary structures consist dominantly of silt-sized to sand-sized planktonic foraminifera tests and shell fragments, indicating frequent storm reworking of these carbonate particles as water depth decreased upward within the parasequence. The distinct decrease in these carbonate-dominated wave ripple and combined-flow ripple laminae, as well as the increase in BI, above the uppermost LST parasequence most plausibly indicates an abrupt relative rise of sea level across a TS.
Regarding the highest carbonate content in this sequence, petrographic observations show that these laminae/beds consist dominantly of planktonic foraminifera tests, which are well-cemented by early diagenetic calcite (Fig. 15D to F). Therefore, the heightened carbonate content directly below the TS in S2 is due to the combined effects of depositional reworking and formation of early diagenetic calcite cement. Nonetheless, it is critical to note that the lithological contrast (high carbonate content) had already been produced as a consequence of depositional processes, and that early diagenesis only amplified an already existing lithological contrast. Therefore, although variations in carbonate content in the lower part of the Tununk Shale (especially S1 and S2) can on first approximation be considered as controlled by clastic dilution, other processes such as reworking by storms and early diagenesis can also have a significant impact on the carbonate content.

In the upper part of the Tununk Shale (S3 to S4), the sediment contribution from primary productivity becomes minor to absent. Layers with high carbonate content in this interval are associated mainly with carbonate concretions and better-cemented layers, and lags of fossil and phosphate fragments. All of these features indicate periods of sediment starvation and can be used to interpret significant flooding events (i.e. TS and MFS). However, without the benefit of parasequence stacking patterns inferred from variations in sedimentary facies and bioturbation characteristics, a TS cannot always be distinguished from a MFS unequivocally based solely on increases in the carbonate content. Moreover, in a situation where only a small amount of carbonate is supplied by primary productivity, overall variability in carbonate content is small as well. This circumstance makes the identification of parasequences based on clastic dilution much more challenging. Therefore, mineralogical proxies have to be integrated with detailed analyses of sedimentary facies, bioturbation and petrographic characteristics, in order to construct robust sequence-stratigraphic frameworks in thick mudstone successions.

High-order relative cycles of sea level during Early to Middle Turonian

The Tununk Shale shows systematic facies variations on varying scales. At least 49 parasequences have been identified in the Tununk Shale in all three measured sections. Based on parasequence stacking patterns, they can be grouped into 11 system tracts and four depositional sequences, revealing a hierarchy of stratigraphic cyclicity recorded in the Tununk Shale.

Vertical variations in lithofacies types and sedimentary facies characteristics indicate that the depositional environment of the Tununk Shale shifted laterally from a distal middle-shelf to an outer-shelf (S1 to S2) setting, and then from an outer-shelf to an inner-shelf environment (S2 to S3, then to S4). These lateral shifts were controlled mainly by the second-order Greenhorn transgressive-regressive sea-level cycle (Leithold, 1994). Similar to other long-term sea-level cycles in the Western Interior Seaway (WIS), the Greenhorn second-order sea-level cycle has been attributed to basin-scale tectonic subsidence (Kaufman, 1985; Gardner, 1995) and can be correlated to the long-term eustatic sea-level cycles during the Late Cretaceous (Haq, 2014).

The presence of four sequences in the Tununk Shale of the study area indicates the superposition of higher-order sea-level changes on the second-order Greenhorn cycle. Constrained by bentonite marker beds and the biostratigraphic framework of Early to Middle Turonian times, the sea-level curve interpreted from the sequence stratigraphic framework of the Tununk Shale (Fig. 22) can be compared with the global eustatic curve. Out of the three sequence boundaries in the Tununk Shale, two (basal SBs of S3 and S4) appear to be globally extensive. The basal SB of S3 is located in the uppermost M. nodosoides Zone, just below the base of the C. woollgari Zone that is commonly used to mark the Lower–Middle Turonian boundary (Fig. 22). A sea level drop (SB) has been identified in the uppermost M. nodosoides Zone in many stratigraphic sections worldwide (Sageman, 1996; Jarvis et al., 2006; Wendler et al., 2016, and references therein). The basal SB of S3 appears to be equivalent to KTu2 of Haq (2014). The basal SB of S4 (Fig. 22) can be correlated to a widely recognized and presumably synchronous sea-level drop (SB) in the middle C. woollgari Zone of the Middle Turonian (Gale, 1996; Sahagian et al., 1996; Miller et al., 2003; Wendler et al., 2016) and appears to correspond to KTu3 in Haq (2014). The basal SB of S2 in the lower M. nodosoides Zone does not appear to correlate with a global sea-level drop, but the possibility of its eustatic nature cannot be entirely excluded from consideration. Unlike the basal SBs of S3 and S4, the basal SB of S2 is
only hinted at by subtle changes in sedimentary facies and bioturbation characteristics without any distinct change in lithofacies. Moreover, the small-amplitude relative fall event of sea level suggested by this SB is superimposed on a long-term global sea-level highstand (Fig. 22). In many stratigraphic sections worldwide this time period is represented by fine-grained hemipelagic to pelagic marlstones or chalks (Jarvis et al., 2006; Wendler et al., 2016). Without detailed analysis of their sedimentological and biogenic features, it can be challenging to identify this SB in fine-grained sedimentary successions. Nevertheless, a SB in the lower *M. nodosoides* Zone has been recorded in Pueblo, Colorado (Sageman, 1996), and in southern New Mexico (Mack et al., 2016). Therefore, the basal SB of S2 at least represents a basin-scale event and potentially marks episodic tectonism (for example, changes in rates of thrusting) in the foreland basin.

At least 49 parasequences are documented in the Tununk Shale in this study. The interval between bentonite marker beds T3 and T10 can be used to estimate the average duration of each parasequence because both the base and top of the Tununk Shale are disconformity surfaces that can only be assigned an approximate age. Based on the stratigraphic position of T3 and T10 in the biostratigraphic framework (Fig. 2), a total of 47 parasequences are recorded within a time span of approximately 2.2 Ma. Thus, the average parasequence duration is *ca* 47 kyr. Considering that it is quite plausible that additional thin parasequences may not have been resolved in this study (note the outliers in Fig. 10), the average duration represented by each parasequence could possibly reflect 41 kyr obliquity cycles (Fischer, 1980). Therefore, the short-term cycles recorded by the parasequences in the Tununk Shale are interpreted to be controlled mainly by the obliquity cycle of the Milankovitch frequency band. The effect of climatic changes driven by Milankovitch cycles has been widely documented in the sedimentary records in the WIS (e.g. Fischer et al., 1985; Elder et al., 1994; Sageman et al., 1997, 1998). Nonetheless, the specific mechanism of how the high-frequency facies variations in these rocks were produced by climatic cycles (for example, changes in freshwater runoff, changes in primary productivity or eustatic sea-level changes) remains controversial (Eldrett et al., 2015; Sames et al., 2016; Wendler et al., 2016). To solve this problem requires more case studies examining the complex variability in fine-grained sedimentary rock successions in detail. Careful correlation of the high-frequency facies variations between different depositional environments in

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the WIS (for example, siliciclastic-input-dominated versus productivity-dominated settings) and other places around the world is critical to fully unravelling the short-term climate and sea-level changes (if any) during the Late Cretaceous.

CONCLUSION

In this study, sequence stratigraphic concepts have been successfully applied to the thick ancient shelf mudstone succession of the Upper Cretaceous Tununk Shale in south-central Utah. Based on detailed analyses of sedimentary facies, bioturbation and petrographic characteristics, at least 49 parasequences can be identified in the Tununk Shale. Each parasequence shows a coarsening-upward trend that is characterized by upward increases in silt and sand content. Silt-sized/sand-sized particles of both siliciclastic and biogenic origins can be considered as ‘detrital’ particles because they are both subject to reworking and concentration by bottom currents. In each parasequence, the thickness and lateral continuity of laminae/beds and abundance of storm-generated sedimentary structures increases upward, indicative of a shallowing-upward trend. Based on parasequence stacking patterns, these parasequences collectively can be grouped into 11 system tracts and four sequences, and key sequence stratigraphic surfaces (i.e. sequence boundaries, transgressive surfaces and maximum flooding surfaces) can be identified.

Parasequences in the Tununk Shale show considerable variability, which is mainly due to changes in dominant sediment supply, depositional processes and bioturbation characteristics. Understanding the changes in rock composition and particle origin is a prerequisite for identification of parasequences in different lithofacies types. In the Tununk Shale, changes of lithofacies types are produced by the lateral shift (changing water depth) of depositional environments on a storm-dominated shelf. This study interprets these changes to have been influenced by a hierarchy of eustatic changes within the second-order Greenhorn tectono-eustatic cycle. The presence of four depositional sequences may reflect the superposition of higher-order sea-level changes superimposed on the second-order Greenhorn cycle. Considering the close correlation with global sea-level events, these short-term sea-level cycles recorded in the Tununk Shale appear to be dominantly controlled by eustatic changes. The average duration of parasequences within the Tununk Shale is estimated to be about 40 kyr, strongly suggesting the obliquity-dominated Milankovitch-scale climatic cyclicity.

Sequence stratigraphic analysis allows the prediction of variations in the lithology, sedimentary facies and bioturbation characteristics in the Tununk Shale on the millimetre-scale to metre-scale. The detailed sequence stratigraphic framework developed in this study helps understanding of the underlying causes of multi-scalar variability and heterogeneity in seemingly homogenous thick mudstone successions. The application of sequence-stratigraphic concepts to such strata requires detailed and integrated analyses of grain size, particle origin, sedimentary structures and biogenic features, because only those properties can directly provide critical information regarding the spatial and temporal evolution of the depositional setting of these rocks.

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